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Preliminary Estimates of Nucleon Fluxes in a Water Target Exposed to Solar-Flare Protons: BRYNTRN Versus Monte Carlo Code

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Abstract

A baryon transport code (BRYNTRN) has previously been verified using available Monte Carlo results for a solar-flare spectrum as the reference. Excellent results were obtained, but the comparisons were limited to the available data on dose and dose equivalent for moderate penetration studies that involve minor contributions from secondary neutrons. To further verify the code, the secondary energy spectra of protons and neutrons are calculated using BRYNTRN and LAHET (Los Alamos High-Energy Transport code, which is a Monte Carlo code). These calculations are compared for three locations within a water slab exposed to the February 1956 solar-proton spectrum. Reasonable agreement was obtained when various considerations related to the calculational techniques and their limitations were taken into account. Although the Monte Carlo results are preliminary, it appears that the neutron albedo, which is not currently treated in BRYNTRN, might be a cause for the large discrepancy seen at small penetration depths. It also appears that the nonelastic neutron production cross sections in BRYNTRN may underestimate the number of neutrons produced in proton collisions with energies below 200 MeV. The notion that the poor energy resolution in BRYNTRN may cause a large truncation error in neutron elastic scattering requires further study.

Introduction

Over the last several years, a family of deterministic radiation transport codes (ref. 1), which were developed at Langley Research Center, have been used as the engineering tool in radiation-shielding analysis for various space missions (refs. 2 to 3). These codes assume the straight-ahead approximation (ref. 4) with the database containing detailed descriptions of the basic physical processes, and yet these codes are computationally efficient (ref. 5) when compared with Monte Carlo codes. One of these deterministic codes (ref. 6), HZETRN (a galactic cosmic-ray transport code), may be the only mature code that is available to estimate the effects from galactic cosmic-ray exposure. The nuclear cross-section database for heavy ions is calculated from semiempirical models that are continuously being improved, whenever high-quality theory or experiments become available. The nucleon portion of the transport code, which is basically BRYNTRN (a baryon transport code), calculates the energy spectra of secondary nucleons (ref. 7), unlike the heavy ion portion in which the energy per unit mass of projectile fragments is approximated by that of the projectile prior to the collision.

Previous BRYNTRN results compared favorably with published Monte Carlo results for one-dimensional solar-proton penetration (ref. 8). The comparison, however, was in terms of dose and dose equivalent rather than detailed energy spectra of secondary nucleons. The contribution of secondary, low-energy neutrons was not a major contributor to the calculated dose for the moderate penetration studies. Therefore, further validation in the individual nucleon spectra is needed for the code to be applicable to deep penetration studies, such as cosmic-ray effects on high-altitude aircraft (ref. 9). In this report, preliminary results from Monte Carlo calculations using LAHET (ref. 10), which were performed at Chalk River Laboratories, are compared with the BRYNTRN nucleon spectra at three depths of a water slab that was exposed to the February 1956 solar flare. Although the comparisons are limited within the selected thicknesses of the water target, the comparison of detailed spectral contributions is a stringent test on the representation of the actual physics involved, and it supports the correct propagation to greater depths.

Monte Carlo Calculation

The LAHET is a Monte Carlo code system used for the transport and interaction of nucleons, pions, muons, light ions, and antinucleons in three-dimensional geometry. It consists of HETC (High-Energy Transport Code) and continuous-energy MCNP (Monte Carlo Neutron Photon code). References 11 and 12 document these codes. The HETC was originally developed at Oak Ridge National Laboratory and modified at Los Alamos National Laboratory to adapt the MCNP surface-geometry package. For the current study, the Bertini intranuclear-cascade model (ref. 13) and the evaporation model of Dresner (ref. 14) are used to describe the physics of nuclear interactions in HETC. A low-energy neutron cutoff of 20 MeV is usually applied in HETC, such that the neutrons with energy below the cutoff are further transported in MCNP using the ENDF/B-5 (ref. 15) data file.

A very large-radius cylinder is used to simulate the one-dimensional slab of water target exposed to the February 1956 solar-flare spectrum. The radius is taken to be 10 m and the depth to be 100 g/cm^2, although only the results at 1-, 10-, and 30-g/cm^2 depths are used to compare with BRYNTRN. The proton spectrum, given in the integral fluence form (protons/cm^2) $\phi_p(>E)$ is

$$\phi_p(>E) = 1.5 \times 10^9 \exp\left(-\frac{E-10}{25}\right) + 3 \times 10^8 \exp\left(-\frac{E-100}{320}\right) \quad (1)$$

where E is the energy in MeV. In this study, the high-energy cutoff is 3 GeV, and the low-energy cutoff is 30 MeV.

The Monte Carlo simulations are conducted at 15 discrete energy points, and the results are summed after having been factored into the number of protons allocated within the energy range (bin) that bounds the energy point (table 1). The input solar-flare spectrum for the 15 energy ranges used in the Monte Carlo calculation, where the discrete energy points are represented by the circles, is shown in figure 1 with the analytical expression. The spectrum presented by the discrete points appears to be slightly lower than that of the analytical curve. The choice of energy bins and of the representative energy points used for the simulations is arbitrary in this situation. Future improvements can be made by increasing the number of energy bins between 50 MeV and 500 MeV and redefining the energy bins that correlate better with the representative energy points. The other alternative for simulating the incident protons is to sample the source distribution function given by equation (1).

BRYNTRN Calculations

The total cross sections for nucleon-nucleon or nucleon-nucleus interactions are reasonably well defined in the literature, and they are easily modeled in the BRYNTRN database, as described in reference 7. However, modeling the differential cross sections related to the secondary nucleon energy spectra is not as straightforward, especially for nonelastic scattering. Modeling for nonelastic scattering was partially derived (ref. 7) from the results of Bertini's intranuclear-cascade code (ref. 16). The quasielastic multiplicity is estimated theoretically (ref. 17), and the low-energy cascade yield is taken from Ranft (ref. 18). The balance of cascade particles is assumed to have a spectral slope that is 30 percent smaller than the low-energy spectrum given by Ranft. (See ref. 7.)

The incident spectrum given by equation (1) with the same high- and low-energy cutoff was input to BRYNTRN. A recently modified version of the code, which allows for a discontinuous nucleon spectrum at the boundary through specialized numerical procedures, was used. This modification allows the transport processes below the low-energy cutoff to be accurately calculated. The run time is less than 2 min on the VAX 4000/500 machine to propagate the solution one dimensionally to a 30-g/cm^2 depth in the water medium. The one-dimensional solution to the Boltzmann equation was a result of assuming the straight-ahead approximation that had been validated earlier by the Monte Carlo results (ref. 19). For neutrons, the backward production and scattering (albedo) must yet be modeled in BRYNTRN.

Results and Discussion

The energy spectra of individual proton and neutron fluence $\phi_n(E)$ calculated using BRYNTRN and the Monte Carlo code for three separate depths (1, 10, and 30 g/cm^2) within a 100-g/cm^2 water slab are compared in figures 2 to 4, respectively. The agreement is good for the protons (figs. 2(a), 3(a), and 4(a)), except at energies below the sudden drop with decreasing energy in the Monte Carlo results; this drop is most obvious at the smallest penetration. The slight overprediction by BRYNTRN in the high-energy region (above the sudden drop) can be accounted for if one considers the underrepresentation of the incident protons by the Monte Carlo calculation, as indicated by figure 1. The large difference below the sudden drop is because only a limited number of discrete energy points were taken for the Monte Carlo simulation. Since the energy of a proton having a range of 1 g/cm^2 in water is approximately 32 MeV, most of the primary protons from the lowest energy bin (30 MeV) would have stopped before 1 g/cm^2, and those protons at 50 MeV (the next bin) would have slowed down to about 35 MeV. The diminished proton population below the sudden drop (fig. 2(a)) arises solely from the secondary protons, and the higher level population predicted by BRYNTRN arises primarily from the slowing down of the primaries that entered the water with energies between 32 and 50 MeV. Those reasonings are substantiated (fig. 5) by a separate calculation for BRYNTRN using a low-energy cutoff for the incident spectrum of 50 MeV. Similar augments can be applied to the large difference seen in figure 3(a) at the 10-g/cm^2 depth, for which a separate calculation with 250-MeV cutoff is displayed in figure 6.

Several issues that need to be resolved are related to the modeling of neutron production and interactions in BRYNTRN. Therefore, an accurate result from the Monte Carlo calculation is crucial in providing a good reference for such modifications in BRYNTRN. The comparisons shown in figures 2(b), 3(b), and 4(b) are only preliminary, but they seem to indicate that the secondary neutrons predicted by BRYNTRN may be too low. The large difference in fluence below 10 MeV seen at 1 g/cm^2, compared with those differences seen at 10 and 30 g/cm^2, is probably an indication of the albedo (i.e., the backward scattered component leaking through the front surface) problem. The backward production and the scattering as related to the albedo affect the neutron spectrum below 10 MeV, and they need to be implemented in the code. At large depths, the low-energy neutron fluence comes into equilibrium with the local collision source, and the neutron flux is isotropic at low energy. At such depths, the straight-ahead flux approaches the three-dimensional result. This effect can be observed by comparing the neutron flux results at 1-, 10,- and 30-g/cm^2 depths, although equilibrium is not expected until approximately 70 g/cm^2. Accurate parameterization of the complex nucleon-nucleus interactions is also necessary for a good estimate of secondary neutron spectra. The BRYNTRN poorly represents the neutron source from proton collisions between 25 and 200 MeV. This poor representation is the source of error in the 10- to 100-MeV neutron flux at 1 g/cm^2. The nonelastic neutron production cross sections in BRYNTRN appear to underestimate current results from the Bertini nuclear interaction model.

Finally, we note that neutrons transfer very little energy in elastic scattering with heavy target constituents. Because the energy resolution in the present BRYNTRN code is poor (30 energy grid points over 4 decades of energy), the small energy loss in elastic scattering may be completely obscured by the truncation errors. Increasing the grid points to accommodate the small energy loss in scattering from heavy target nuclei is impractical, and new numerical procedures are required. Clearly, these issues need to be further examined in future research.

Two different approaches in treating the input spectrum to the Monte Carlo calculation were mentioned above. Sampling the source distribution has the advantage of eliminating the inaccuracy caused by discretizing the energy, while the latter has the advantage of saving the single-energy results for any future use. Discretizing the energy can be a good choice for the future work when an elaborate interpolation method with scaling quantities that preserve the physics of nuclear interaction is employed.

Concluding Remarks

Preliminary comparisons of nucleon spectra calculated by BRYNTRN (a baryon transport code) and the Monte Carlo code were made at three depths of a water slab exposed to a solar-flare spectrum. Reasonable agreements were obtained when various considerations related to the calculational techniques and limitations were taken into account. Although the Monte Carlo results are preliminary, it appears that the neutron albedo, which is not currently treated in BRYNTRN, might be a cause for the large discrepancy in neutron fluence at low energies seen at the small penetration. It also appears that the nonelastic neutron production cross sections for proton impact between 25 and 200 MeV in the BRYNTRN code may underestimate current results from the Bertini nuclear interaction model. Finally, the notion that the poor energy resolution in BRYNTRN may cause a large truncation error in neutron elastic scattering needs to be examined further. Additional improvements in Monte Carlo calculations are needed to provide a finer reference for assessing the BRYNTRN results.

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Table 1. Input Proton Fluences Within Assumed Energy Bins
and Simulated Energy Values

Bin number	Low-energy bound, MeV	High-energy bound, MeV	Simulated energy, MeV	Fluence, particle/cm^2
1	20	40	30	4.33×10^8
2	40	60	50	2.04×10^8
3	60	140	100	2.03×10^8
4	140	360	250	1.05×10^8
5	360	640	500	5.86×10^7
6	640	860	750	2.08×10^7
7	860	1140	1000	1.23×10^7
8	1140	1360	1250	4.36×10^6
9	1360	1640	1500	2.57×10^6
10	1640	1860	1750	9.14×10^5
11	1860	2140	2000	5.38×10^5
12	2140	2360	2250	1.91×10^5
13	2360	2640	2500	1.13×10^5
14	2640	2860	2750	4.01×10^4
15	2860	3140	3000	2.37×10^4

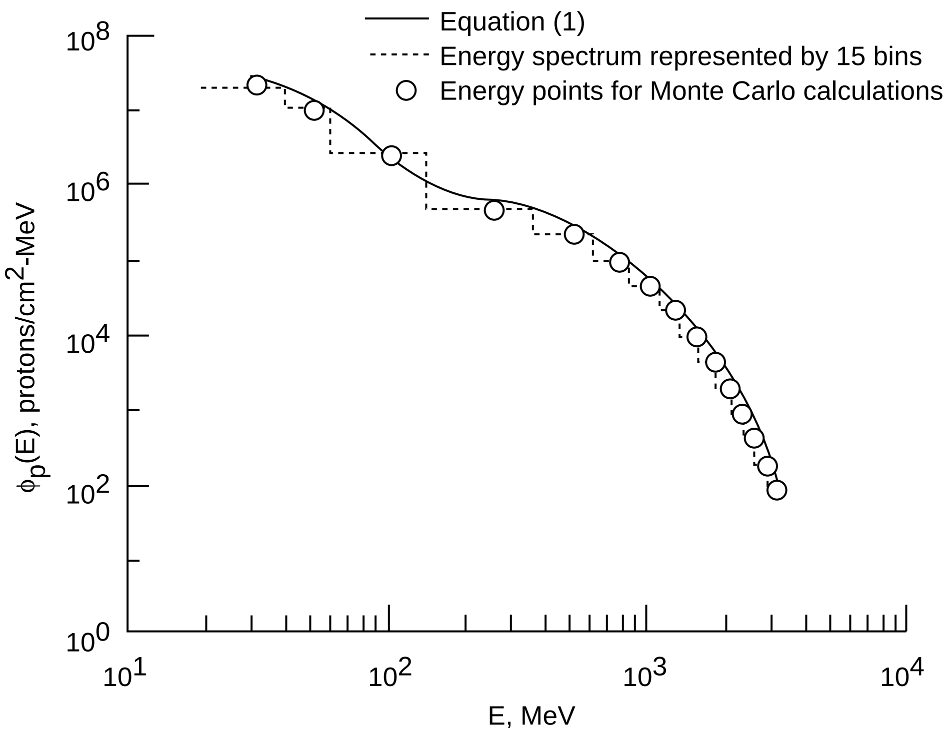
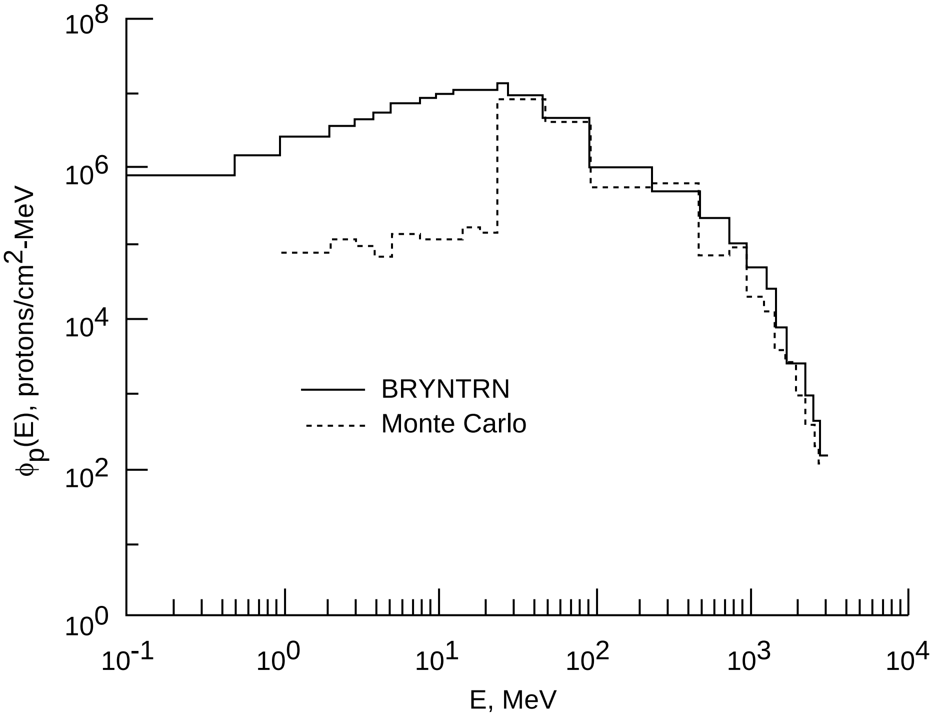
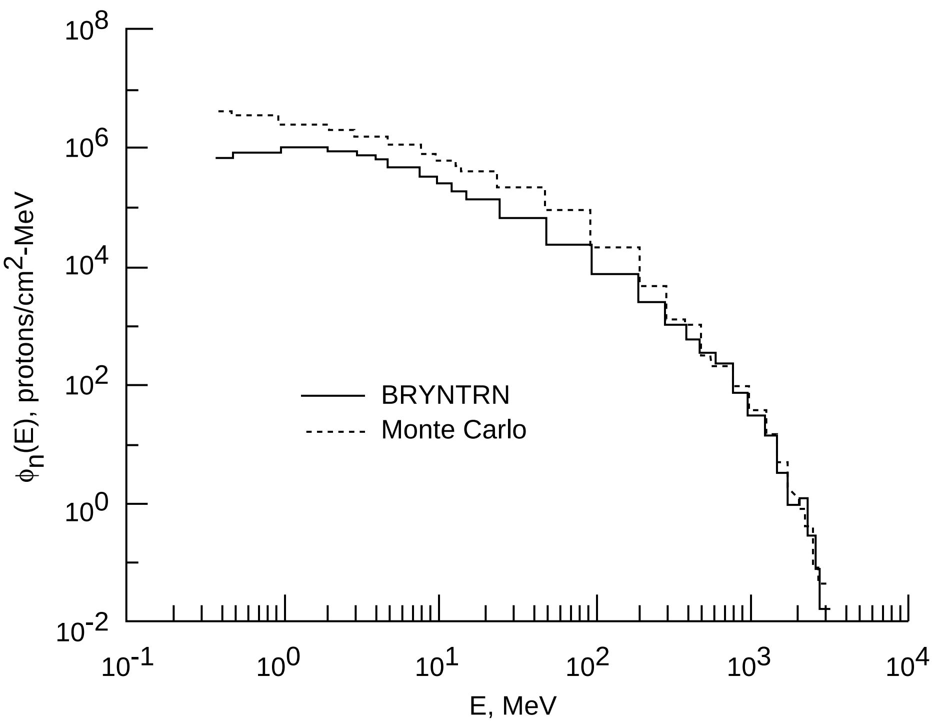


Figure 1. Differential spectrum of February 1956 solar flare.

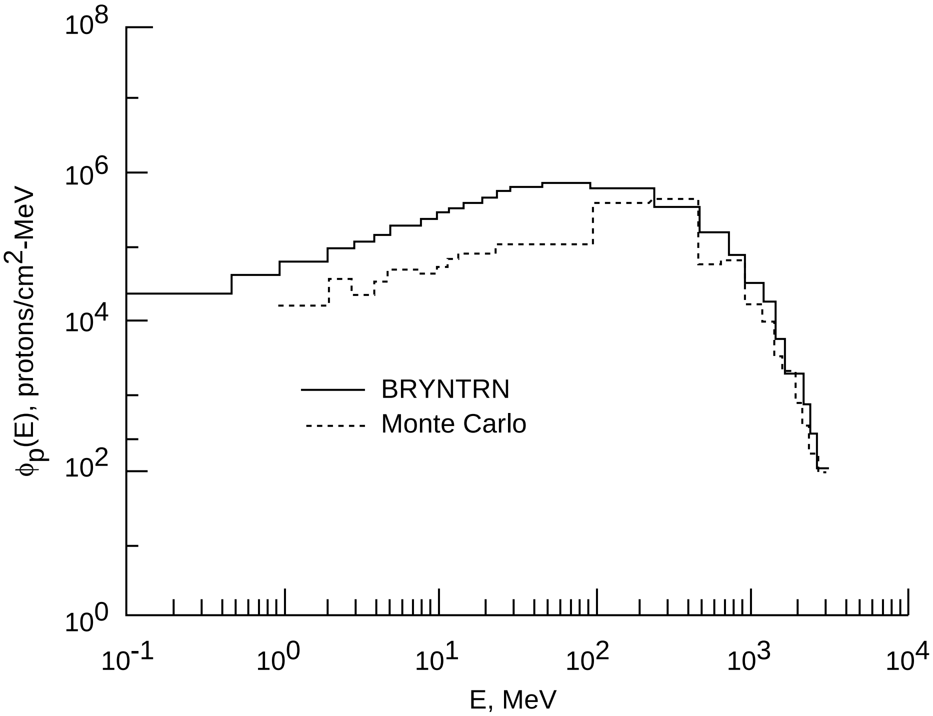


(a) Proton fluence.

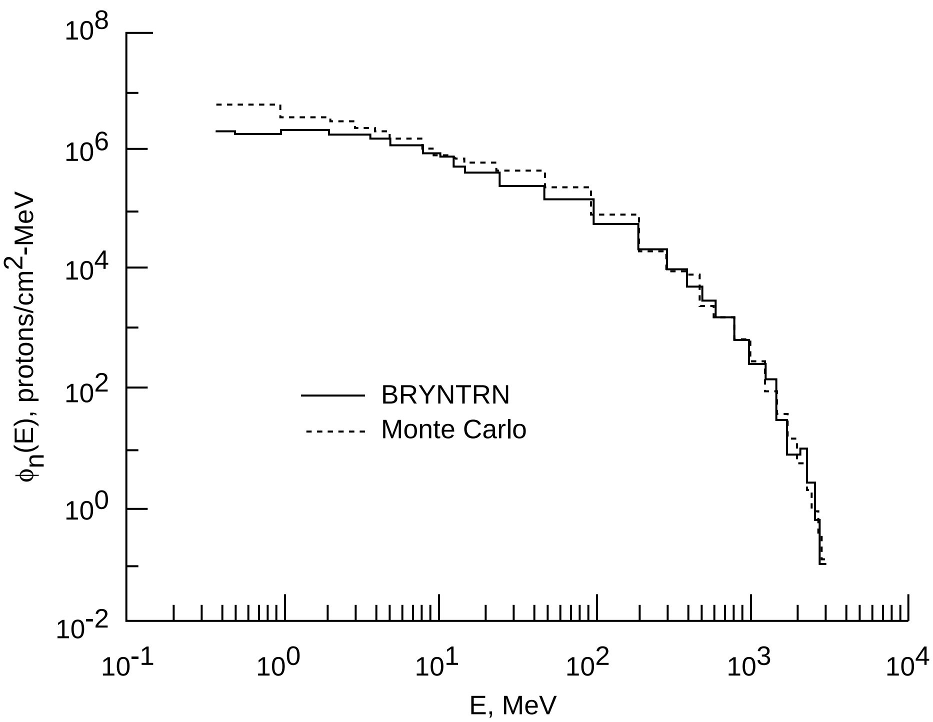


(b) Neutron fluence.

Figure 2. Energy spectra of nucleon fluences at 1-g/cm^2 depth of water slab exposed to February 1956 solar flare, as calculated using BRYNTRN and LAHET.

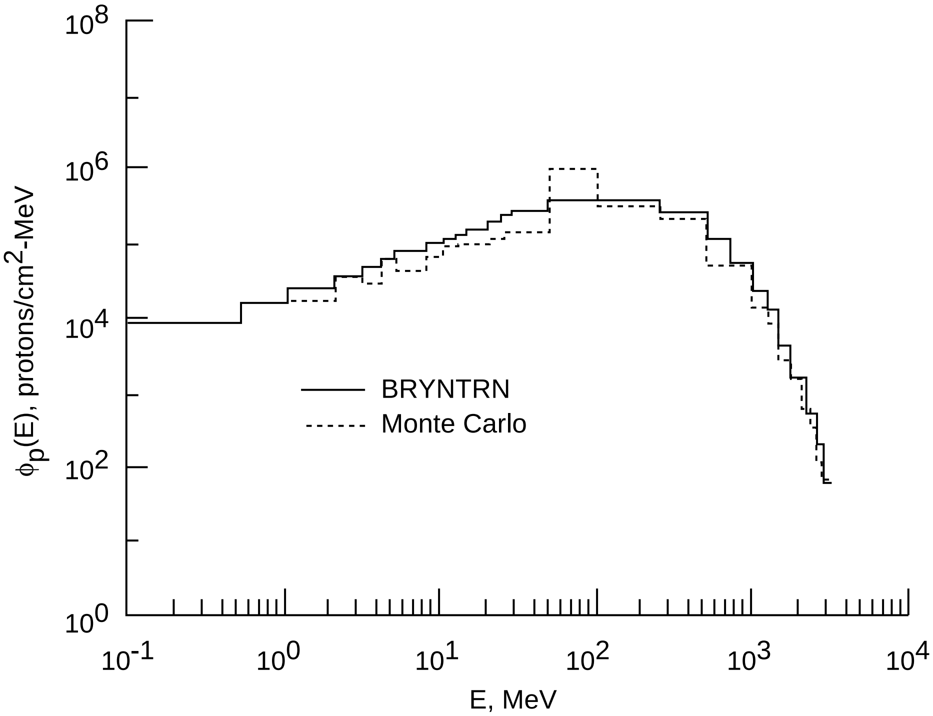


(a) Proton fluence.

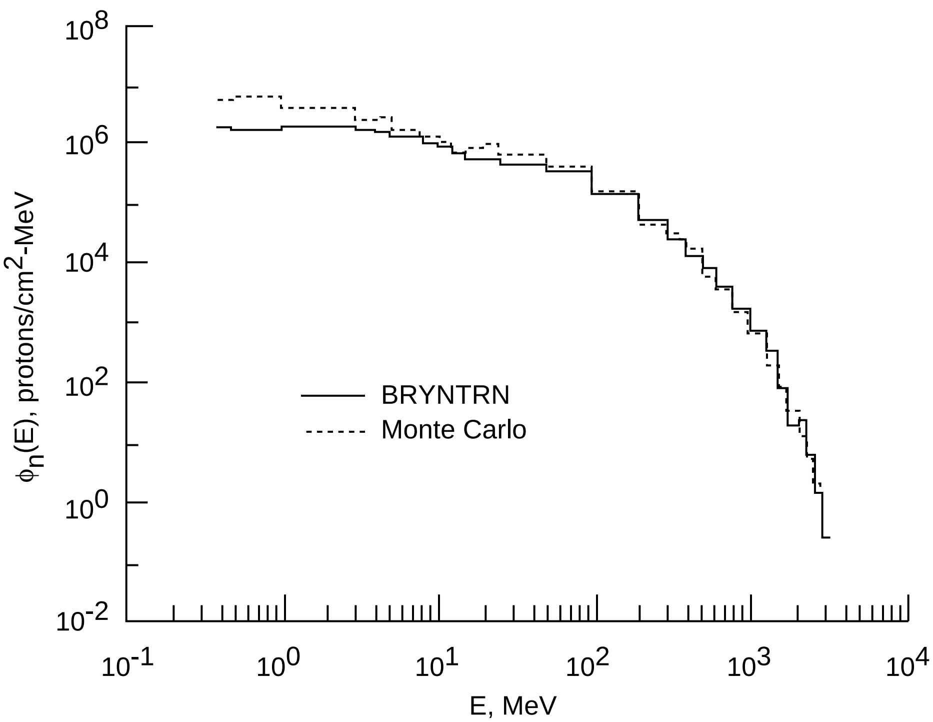


(b) Neutron fluence.

Figure 3. Energy spectra of nucleon fluences at 10-g/cm^2 depth of water slab exposed to February 1956 solar flare, as calculated using BRYNTRN and LAHET.



(a) Proton fluence.



(b) Neutron fluence.

Figure 4. Energy spectra of nucleon fluences at 30-g/cm^2 depth of water slab exposed to February 1956 solar flare, as calculated using BRYNTRN and LAHET.

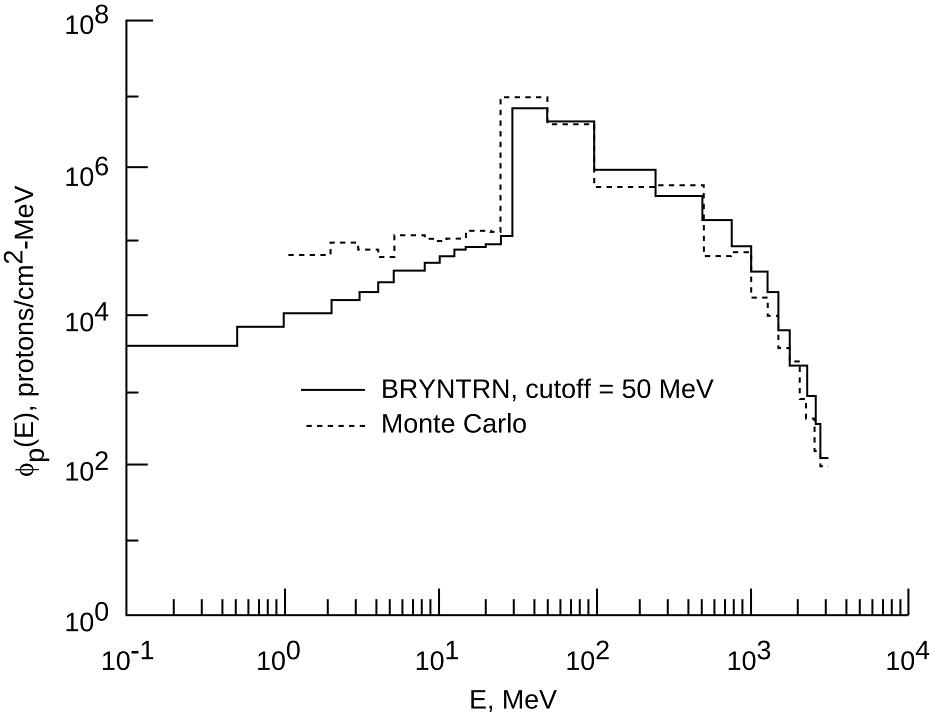


Figure 5. Energy spectra of proton fluences at 1-g/cm^2 depth of water slab exposed to February 1956 solar flare, as calculated using LAHET and BRYNTRN with 50-MeV low-energy cutoff.

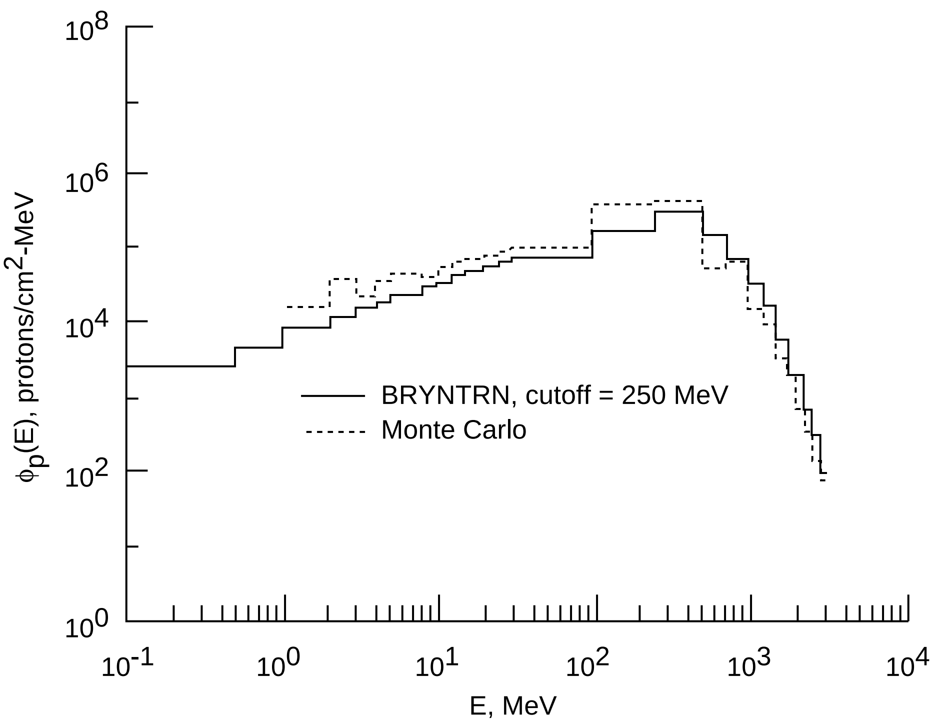


Figure 6. Energy spectra of proton fluences at 10-g/cm^2 depth of water slab exposed to February 1956 solar flare, as calculated using LAHET and BRYNTRN with 250-MeV low-energy cutoff.

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13. ABSTRACT *(Maximum 200 words)*
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